Supplement of

Spatiotemporal dynamics of atmospheric CO_2 across China revealed by long-term, high-resolution satellite-derived data

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Table S1. Summary of multi-source datasets used in the fusion model.

Category	Data name	Spatial resolution	Temporal frequency	Time coverage	Data source
Satellite observation	OCO-2 XCO_2	1.29 km ×2.25 km	16days	2014 to 2022	https://disc.gsfc.nasa.gov/
Reanalyzed XCO_2	Carbon Tracker	3°×2°	3-hourly	2000 to 2020	https://gml.noaa.gov/
Air pollution	MERRA2-GMI	0.5°×0.625°	hourly	1980 to 2018	https://acd-ext.gsfc.nasa.gov/
	EAC4	0.75°×0.75°	3-hourly	2003 to 2024	https://ads.atmosphere.copernicus.eu/
	MAIAC AOD	0.01°×0.01°	daily	2000 to 2020	https://dataverse.harvard.edu/dataverse/atmospheric_data_by_WHUT
	ERA	0.125°×0.125°	6-hourly	1979 to 2019	https://apps.ecmwf.int/
Meteorological covariates	ERA5	0.25°×0.25°	hourly	1940 to 2025	https://cds.climate.copernicus.eu/
	TRIMS LST	1km×1km	daily	2000 to 2020	https://data.tpdc.ac.cn/
Geographic variables	MOD13A3	1km×1km	monthly	2000 to 2025	https://ladsweb.modaps.eosdis.nasa.gov/
	CLCD	30m×30m	yearly	1990 to 2023	https://zenodo.org/
	ASTER GDEM	30m×30m	-	-	http://gdex.cr.usgs.gov/
	LandScan	30m×30m	yearly	2000 to 2023	https://landscan.ornl.gov/

Table S2. Data source of potential predictors for long-term XCO_2 estimation modeling (* indicates this variable was finally used for fusion modeling).

Full name	Abbreviation	Spatial resolution	Temporal frequency	Time coverage	Data source
CarbonTracker XCO_2	CTxco2_lst*	3°×2°	3-hourly	2000-2020	https://gml.noaa.gov/
Land surface temperature	lst_trims_day*	1km×1km	daily	2000-2020	Thermal and Reanalysis Integrating Moderate-resolution Spatial-seamless (https://cstr.cn/18406.11.Meteoro.tpdc.271252/)
Cropland	LUCT1*	30m×30m	yearly	2000-2020	https://zenodo.org/records/5816591/
Forest	LUCT2				
Shrub	LUCT3				
Grassland	LUCT4*				
Water	LUCT5				
Sonw/Ice	LUCT6				
Barren	LUCT7				
Impervious	LUCT8				
Wetland	LUCT9				
Digital elevation model	DEM*	30m×30m	-	-	http://gdex.cr.usgs.gov/
Normalized difference vegetation index	NDVI*	1km×1km	monthly	2000-2020	https://ladsweb.modaps.eosdis.nasa.gov/
Population	Population*	30m×30m	yearly	2000-2020	https://landscan.ornl.gov/
Total column nitrogen dioxide	no2_daily*	0.5°×0.625°/0.75°×0.75°	hourly/3-hourly	2000-2003 /2003-2020	https://acd-ext.gsfc.nasa.gov/ https://ads.atmosphere.copernicus.eu/
Total column peroxyacetyl nitrate	nitrate_daily*				
Total column nitric acid	hno3_daily_EAC4				
Total column nitrogen monoxide	no_daily_EAC4				
Aerosol optical depth	MAIAC_AOD*	0.01°×0.01°	daily	2000-2020	Multi-Angle Implementation of

					Atmospheric Correction (https://dataverse.harvard.edu/dataverse/atmospheric_data_by_WHUT)
Boundary layer height	blh*	0.125°×0.125°/	6-hourly/hourly	2000-2019/	https://apps.ecmwf.int/
Evaporation	e*	0.25°×0.25°		2019-2020	https://cds.climate.copernicus.eu/
Surface pressure	sp*				
TOA incident solar radiation	tisr*				
Surface thermal radiation downwards	strd*				
Total column water vapour	tcwv*				
10 metre U wind component	u10*				
10 metre V wind component	v10*				
Total column ozone	tco3*				
2m dewpoint temperature	d2m				
High cloud cover	hcc				
Medium cloud cover	mcc				
Low cloud cover	lcc				
Total cloud cover	tcc				
Total column water	tcw				
Skin temperature	skt				
Surface latent heat flux	slhf				
Surface sensible heat flux	sshf				
Surface net solar radiation	ssr				
Surface net solar radiation, clear sky	ssrc				
Surface solar radiation downwards	ssrd				

Surface net thermal radiation	str				
Surface net thermal radiation, clear sky	strc				
2 metre temperature	t2m				
Total precipitation	tp				
Top net solar radiation	tsr				
Top net solar radiation, clear sky	tsrc				
Top net thermal radiation	ttr				
Top net thermal radiation, clear sky	ttrc				
Longitude	lon*	-	-	-	Constructed auxiliary variables
Latitude	lat*				
Day of year	DOY*				

Table S3. Ground-based monitoring sites used in this study.

Monitoring sites	Station	Latitude	Longitude	Period	Temporal frequency	Spatial resolution	Data source
TCCON	HF	31.9°N	117.17°E	2015 - 2020	hourly	Point	https://tccondata.org/
	XH	39.8°N	116.96°E	2018 - 2020			
WDCGG	WLG	36.28°N	100.9°E	2000 - 2020	daily	Point	https://gaw.kishou.go.jp/

Table S4. CV results at seven geographic regions.

Geographical regions	Sample 10-fold CV			Spatial 10-fold CV			Time 10-fold CV		
	R^2	RMSE (ppm)	MAE (ppm)	R^2	RMSE (ppm)	MAE (ppm)	R^2	RMSE (ppm)	MAE (ppm)
Central China	0.98	0.70	0.51	0.98	0.70	0.51	0.91	1.45	1.12
East China	0.97	0.73	0.52	0.97	0.73	0.52	0.91	1.35	1.04
North China	0.99	0.61	0.43	0.99	0.61	0.44	0.95	1.12	0.85
Northeast China	0.96	1.14	0.50	0.96	1.14	0.50	0.92	1.63	0.94
Northwest China	0.97	0.76	0.52	0.97	0.76	0.52	0.94	1.21	0.92
South China	0.97	0.85	0.62	0.97	0.85	0.62	0.92	1.41	1.09
Southwest China	0.94	1.06	0.76	0.95	1.06	0.77	0.91	1.39	1.05

Table S5. Independent validation results of daily XCO_2 values vs. ground-based observations.

Station	No. of matchup	R^2	RMSE (ppm)	MAE (ppm)
HF	294	0.92 (1×1)	1.22 (1×1)	0.97 (1×1)
		0.92 (10×10)	1.23 (10×10)	0.97 (10×10)
		0.92 (100 ×100)	1.23 (100 ×100)	0.97 (100 ×100)
XH	578	0.82 (1×1)	1.69 (1×1)	1.29 (1×1)
		0.82 (10×10)	1.68 (10×10)	1.28 (10×10)
		0.82 (100 ×100)	1.66 (100 ×100)	1.27 (100 ×100)
WLG	6356	0.97 (1×1)	2.90 (1×1)	2.48 (1×1)
		0.97 (10×10)	2.88 (10×10)	2.47 (10×10)

Table S6. Statistics of daily correlation coefficients between our estimates and other XCO_2 data.

XCO_2 datasets	Mean	STD	MAX	MIN
CT	0.89	0.32	0.98	0.51
CAMS	0.69	0.46	0.93	0.32
GOSAT	0.56	0.40	0.90	0.32

Table S7. Performance comparison of models with various structures.

Variables	Sample 10-fold CV			Spatial 10-fold CV			Leave-one-year out CV		
	R^2	RMSE	MAE	R^2	RMSE	MAE	R^2	RMSE	MAE
Residual model (Replace CT with total_emi_CO_2)	0.97	0.78	0.53	0.97	0.78	0.53	0.24	4.52	3.81
Residual model (Replace CT with fff_emi_CO_2)	0.97	0.77	0.53	0.97	0.77	0.53	0.24	4.50	3.80
Use CT as predictor	0.98	0.75	0.52	0.98	0.76	0.52	0.89	1.87	1.45

total_emi_CO2 represents the annual total CO_2 emissions, while fff_emi_CO_2 specifically denotes emissions from fossil fuel combustion. Both datasets are sourced from Emissions Database for Global Atmospheric Research version (EDGAR) v7.0.

Table S8. Statistics of OCO-2 XCO_2 observations in Zhoushan, Ningbo, Jiaxing, Shanghai.

Period		Zhoushan		Ningbo		Jiaxing		Shanghai	
		XCO_2	Count	XCO_2	Count	XCO_2	Count	XCO_2	Count
2015	Year	403.37	58	400.3	75	399.04	8	402.02	184
	Spring	403.52	56	403.69	36	402.56	3	403.46	73
	Summer	398.98	2	395.45	20	396.24	4	-	-
	Autumn	-	-	399.01	19	399.69	1	-	-
	Winter	-	-	-	-	-	-	401.08	111
2016	Year	406.05	1	406.43	201	405.98	60	405.66	466
	Spring	-	-	406.19	52	405.56	25	-	-
	Summer	406.05	1	-	-	-	-	-	-
	Autumn	-	-	-	-	-	-	-	-
	Winter	-	-	406.52	149	406.28	35	405.66	466
2017	Year	-	-	408.8	837	409.06	171	408.72	281
-	Spring	-	-	409.42	423	409.92	90	409.7	77
	Summer	-	-	407.3	69	-	-	407.19	19
	-	-	-	-	-	-	-	-	-
	Winter	-	-	408.35	345	408.11	81	408.47	185
2018	Year	-	-	408.14	251	408.77	168	408.94	149
	Spring	-	-	410.99	9	412.04	18	409.00	140
	Summer	-	-	407.98	238	408.27	145	407.95	9
	Autumn	-	-	411.22	4	-	-	-	-
	Winter	-	-	-	-	411.44	5	-	-
2019	Year	412.66	7	412.98	666	414.08	175	414.03	115
	Spring	412.66	7	413.71	323	414.52	80	413.91	57
	Summer	-	-	408.43	5	413.95	6	-	-
	Autumn	-	-	411.68	196	413.42	64	412.12	9
	Winter	-	-	413.28	142	414.41	25	414.52	49
2020	Year	417.47	1	414.54	344	413.77	110	414.65	184
	Spring	417.47	1	417.22	86	416.82	15	-	-
	Summer	-	-	413.1	171	412.13	45	415.45	1
	Autumn	-	-	412.63	40	413.79	34	414.46	145
	Winter	-	-	416.46	47	415.47	16	415.36	38

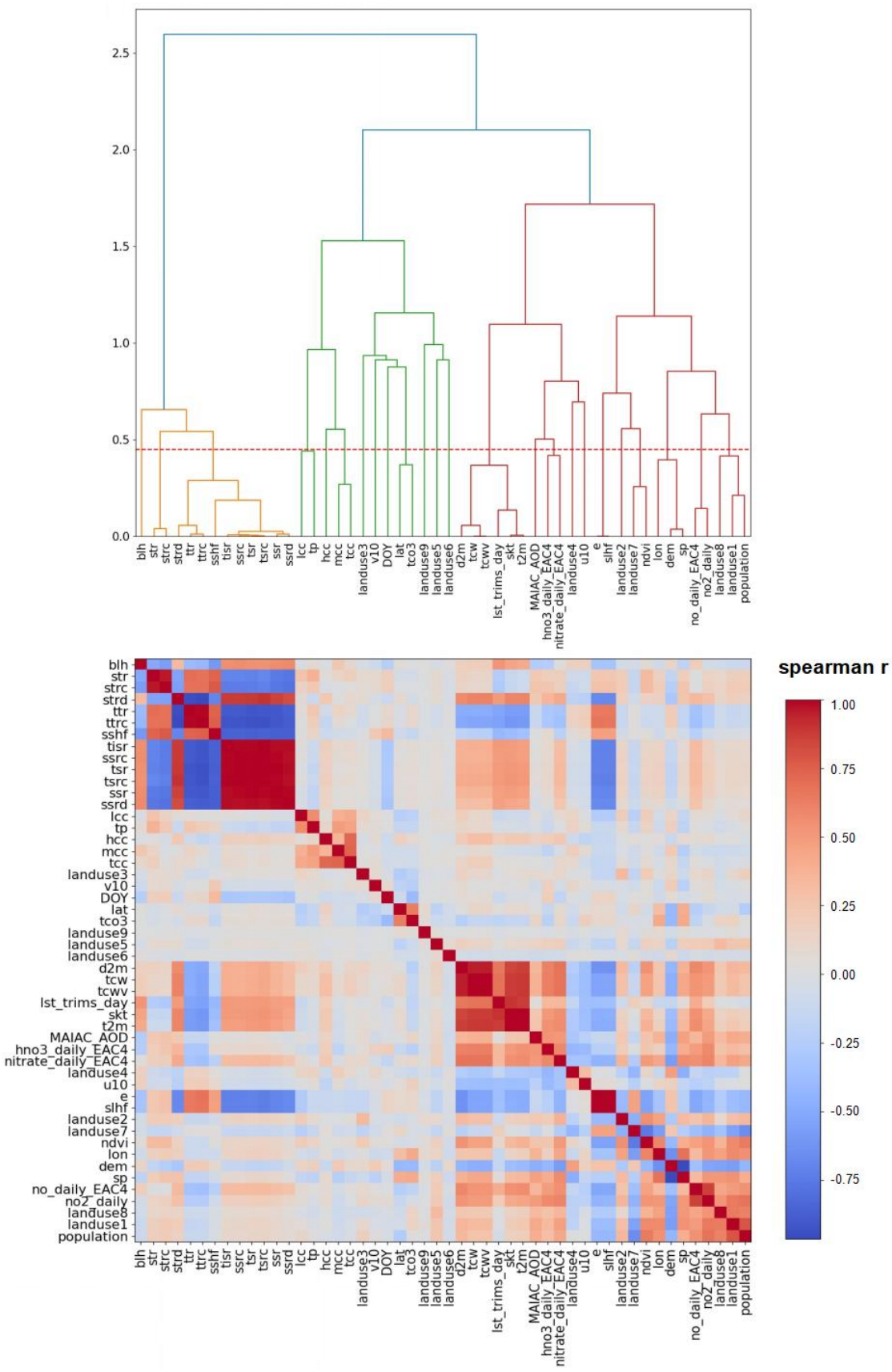

Figure S1. Heat map of explanatory variables.

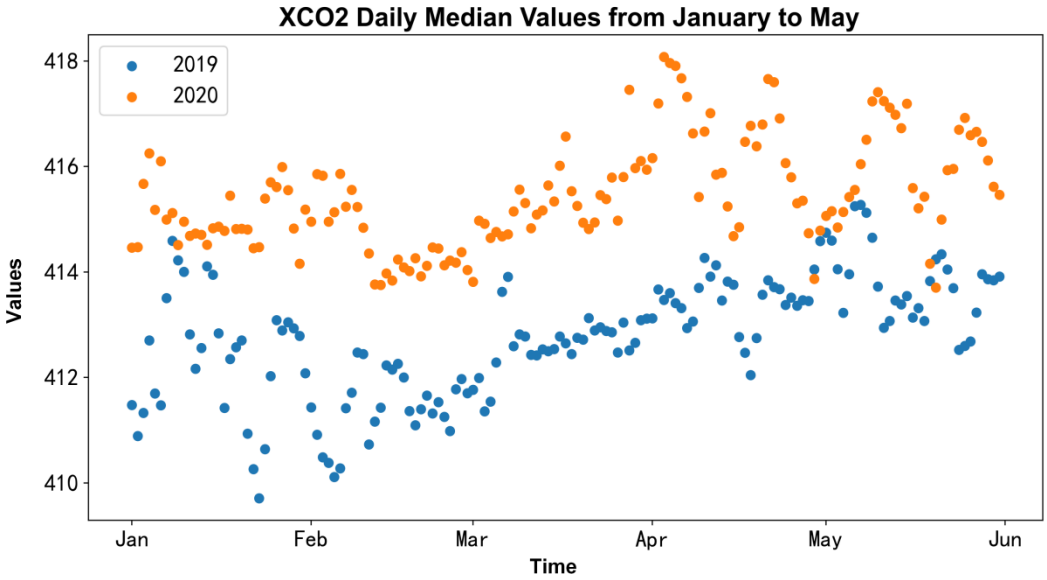

Figure S2. XCO_2 daily median over the Wuhan lockdown due to the COVID-19 outbreak in 2020, with the same periods in 2019 included for comparison.

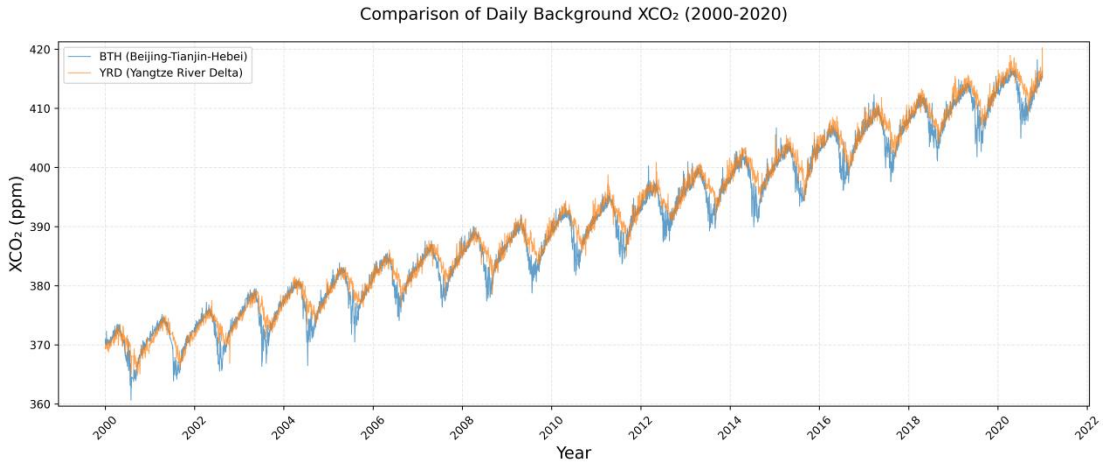

Figure S3. XCO_2 daily background for the (a) Beijing-Tianjin-Hebei region and (b) the Yangtze River Delta region from 2000 to 2020.

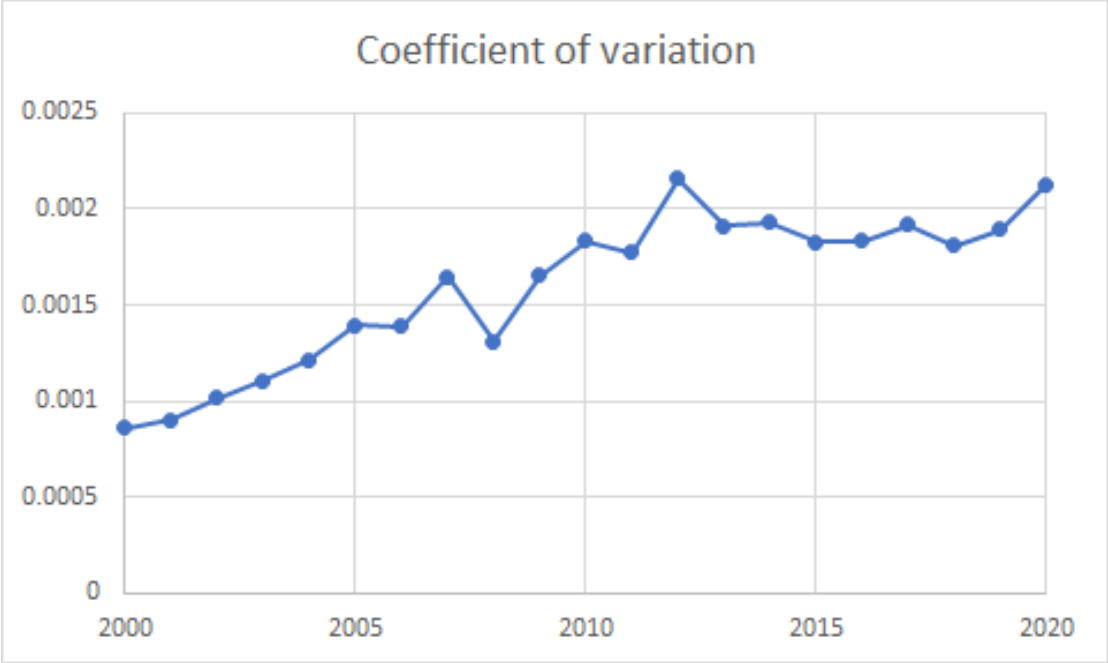

Figure S4. Coefficients of variation for annual mean XCO_2 across China from 2000 to 2020.

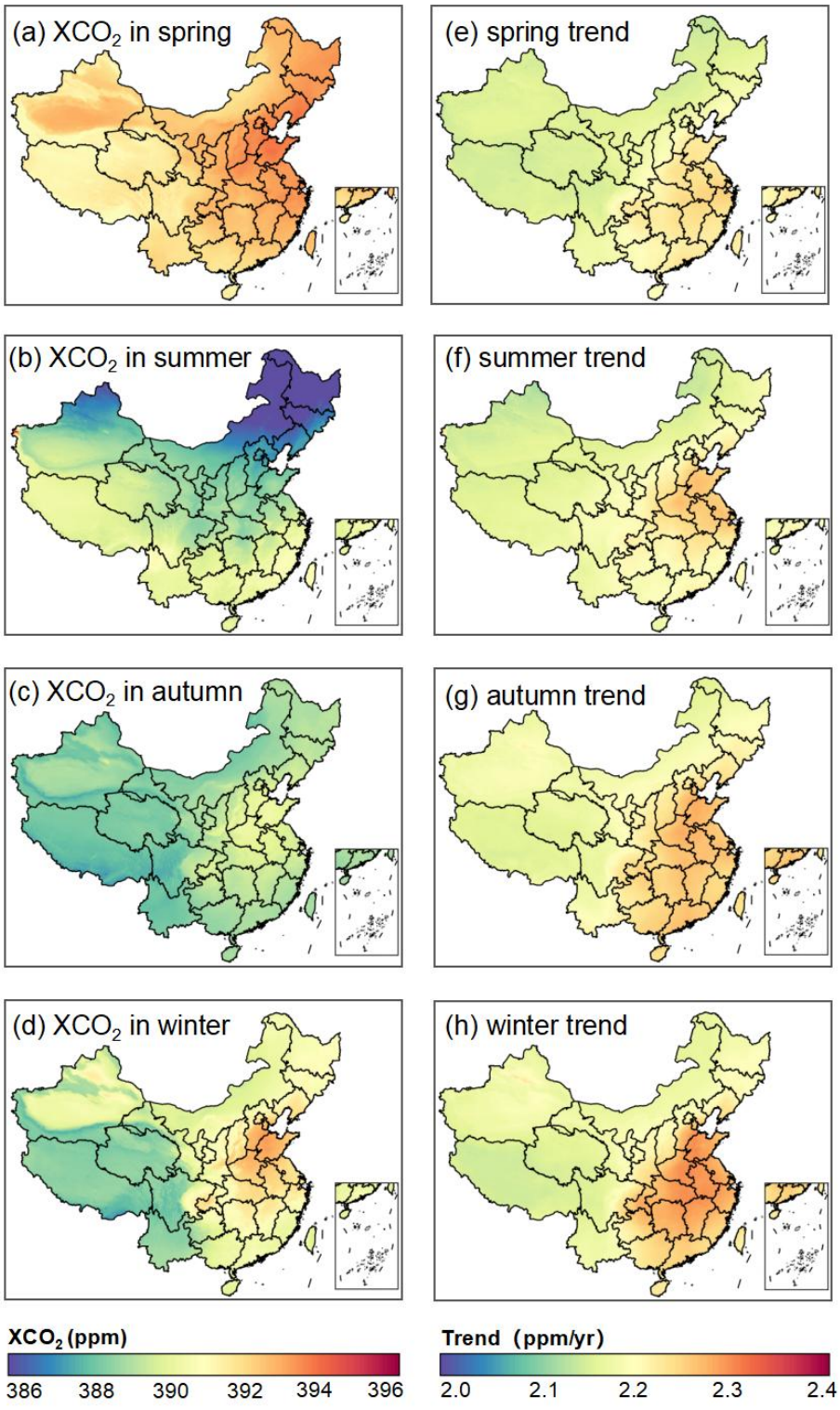

Figure S5. Spatial distribution of seasonal mean 1-km XCO_2 and their linear trends in China over the period 2000-2020.

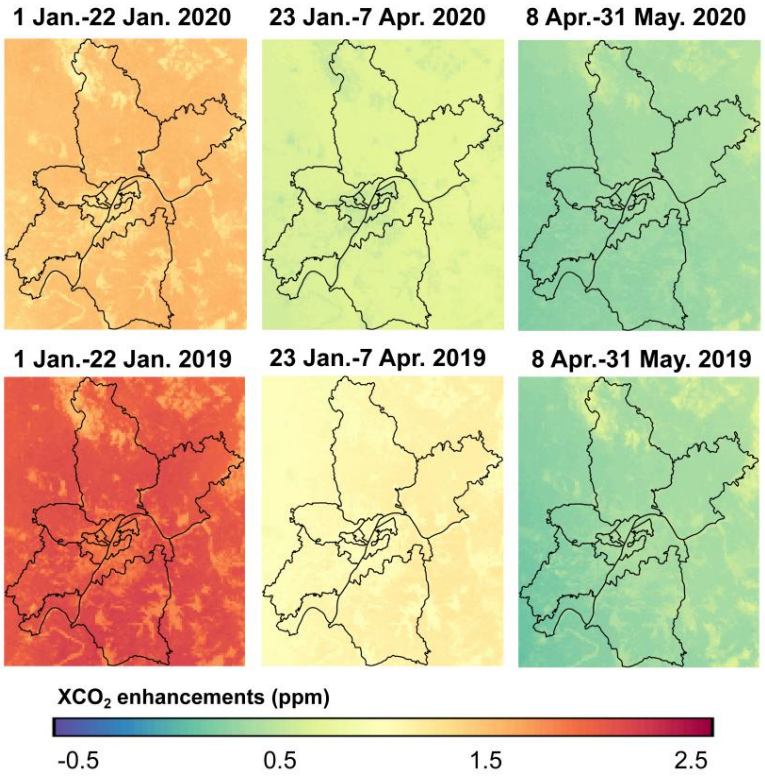

Figure S6. Spatial patterns of mean XCO_2 enhancements before (Jan 1–22), during (Jan 23–Apr 7), and after (Apr 8–May 31) the Wuhan lockdown due to the COVID-19 outbreak in 2020, with the same periods in 2019 included for comparison.

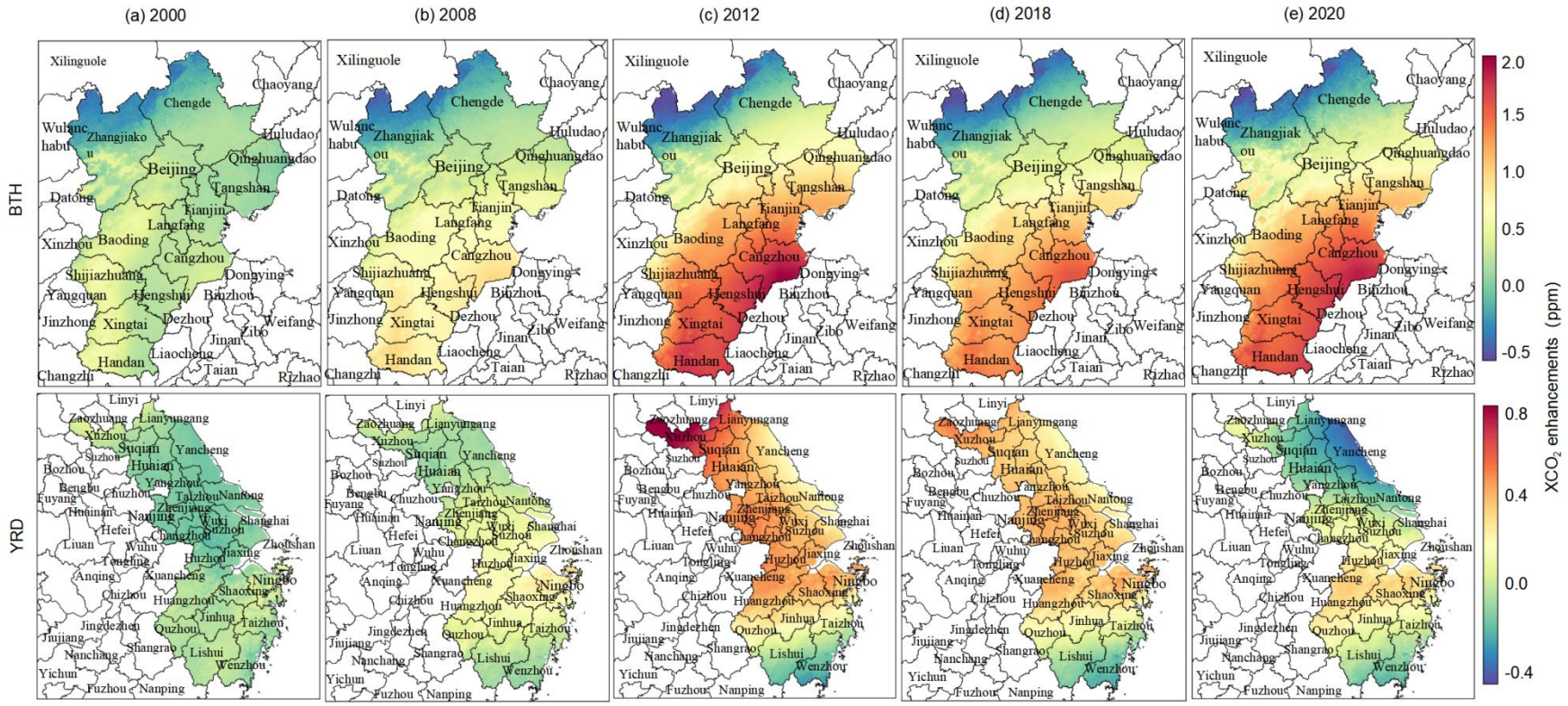

Figure S7. Spatial distribution of annual mean XCO_2 enhancements (ppm) in the BTH and YRD regions.

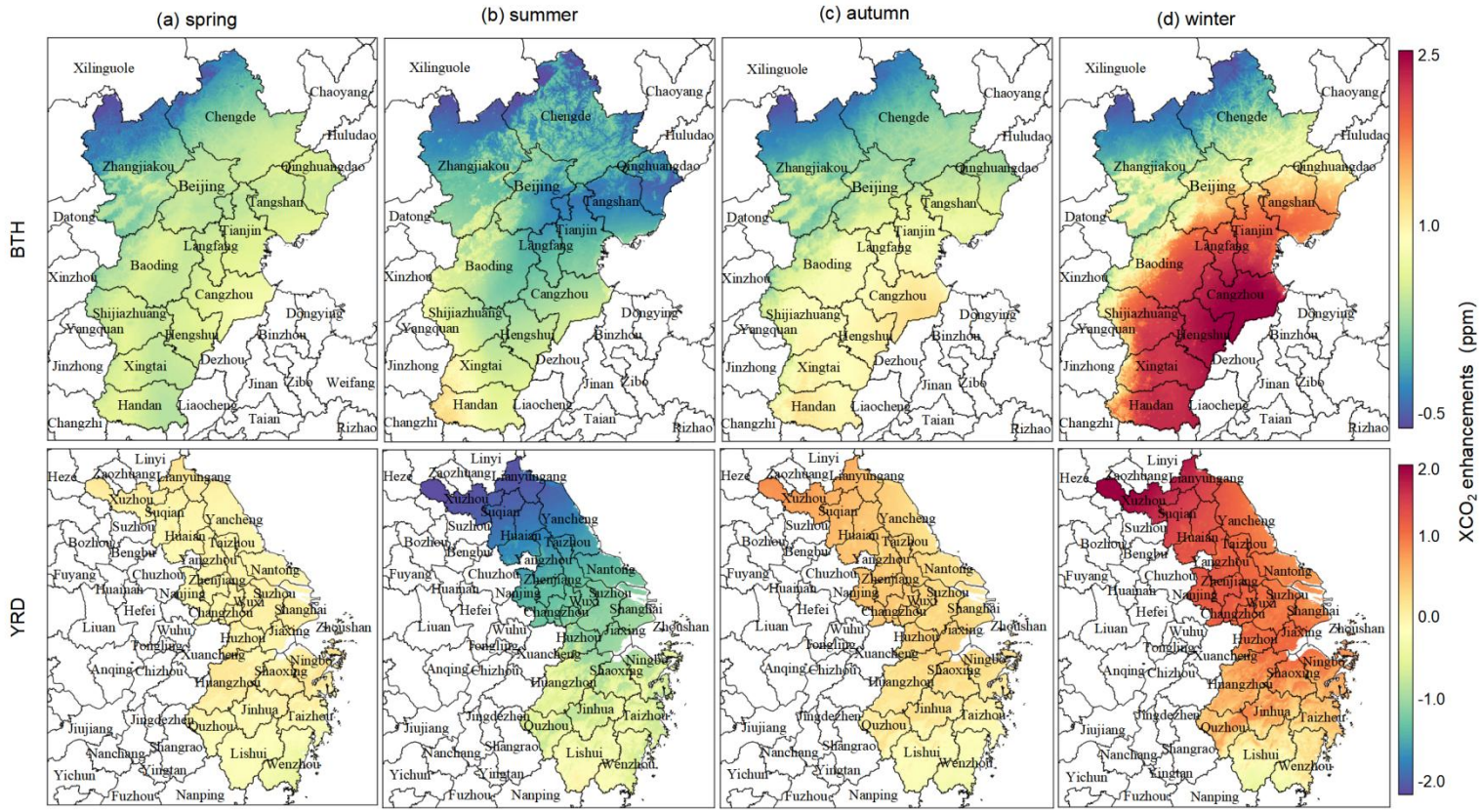

Figure S8. Spatial distribution of seasonal mean XCO_2 enhancements (ppm) in the BTH and YRD regions from 2000 to 2020.